

Fast terahertz imaging using a quantum cascade amplifier

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A terahertz (THz) imaging scheme based on the effect of self-mixing in a 2.9 THz quantum cascade (QC) amplifier has been demonstrated. By coupling an antireflective-coated silicon lens to the facet of a QC laser, with no external optical feedback, the laser mirror losses are enhanced to fully suppress lasing action, creating a THz QC amplifier. The addition of reflection from an external target to the amplifier creates enough optical feedback to initiate lasing action and the resulting emission enhances photon-assisted transport, which in turn reduces the voltage across the device. At the peak gain point, the maximum photon density coupled back leads to a prominent self-mixing effect in the QC amplifier, leading to a high sensitivity, with a signal to noise ratio up to 55 dB, along with a fast data acquisition speed of 20,000 points per second.

Terahertz (THz) wave imaging holds great promise for many applications, such as biomedical sensing, security control, non-destructive analysis and spectroscopic mapping^{1,2}. In recent years, quantum cascade (QC) lasers have proved to be a compact, coherent source in the THz spectral region³. Based on the emission driven from electron transitions between individual subbands within the conduction band of a semiconductor heterostructure, THz QC lasers have demonstrated emission frequencies from 1.2 to 5.2 THz⁴. Peak power over 1 W in pulsed mode and more than 100 mW in cw mode have been reported^{5,6}. High output power as well as high spectral purity from QC lasers facilitates high dynamic range imaging systems with the potential to study highly attenuating samples as well as investigations over long distances⁷. Recently, a THz imaging system based on a single QC laser serving as both the source and the detector has been reported⁸. By coupling the radiation back into the laser cavity, the reflected light, containing information on the target object, interferes with the intra-cavity field and in turn provides perturbation in the laser dynamics. This results in changes in the optical and electrical properties of the device, which includes the variations in the emission power of the laser, lasing spectrum⁹, optical gain and also the voltage across the device, and is described as the self-mixing effect¹⁰. Various metrological quantities of the objects can be characterized through this self-mixing interferometry technique by recording the perturbation in the voltage across the laser, such as the target object's reflectivity, velocity, and also angular displacement. An advantage for such a technology is that no additional detector is required, which makes the optical scheme relatively straightforward and compact. This unique advantage provides particular benefits at THz frequencies, due to a lack of sensitive and compact coherent detection schemes. Moreover, the acquisition rate of a THz imaging scheme is commonly limited due to the relatively slow response time of typical THz detectors (1-100 ms), such as Golay cell detectors, pyroelectric detectors and other cryogenically cooled detectors⁷. Recently demonstrated was a fast detection scheme based on a deflecting mirror with a fast Ge:Ga photoconductive detector, an acquisition rate up to 4,140 points per second (pps) was achieved¹¹. Self-mixing detection schemes based on QC lasers hold the potential to achieve faster acquisition rates, since in principle the response time is only determined by the optical feedback

response bandwidth of QC devices, which is up to 20 GHz, as demonstrated in Ref. 12. Self-mixing interferometry based on QC lasers has emerged as a powerful sensing technique at THz frequencies. Promising progress has been achieved with regards to imaging applications⁷, including displacement sensing¹³, and three-dimensional imaging¹⁴. Moreover this coherent detection scheme has also been extended to other research areas such as the study of intrinsic stability of QC lasers¹⁵ and imaging of free carriers on the surface of semiconductors in the THz frequency region¹⁶. In the self-mixing experiment, voltage perturbation due to optical feedback, which is the difference in the voltage across the laser in the case of no feedback, and the case of maximal feedback, is directly related to photon-assisted transport. Therefore, a larger amount of photon density coupled back will induce a larger voltage perturbation across the device. However, in all the previous work based on stand-alone lasers^{7,8}, both the uncoated facet reflectivity (32% at GaAs and air interface) as well as the divergent far-field beam pattern constrained the amount of photon density coupled back to the laser. As a result, all the devices were driven just above threshold and operated in cw mode, where the change of the threshold gain was directly related to the feedback element, and led to a change in the voltage across the terminals. Therefore, the constrained amount of light coupled back prevents the benefit of the favorable gain of QC lasers being exploited, where at the peak gain point, the maximum photon density coupled back will induce maximum sensitivity. In turn this limited sensitivity also prevents the fast response of QC lasers being fully demonstrated. Furthermore, cw operation also constrains the high temperature operating conditions for the device. Consequently, a mechanical chopper⁸ or an electrical modulation signal on top of a dc driving current¹⁷ are required, in all the previous work based on the stand-alone lasers.

As demonstrated in Ref. 18, a high gain terahertz amplifier was achieved by adapting a 2.9 THz QC laser. By depositing an antireflective (AR) coating on the laser facet, the optical feedback and lasing action were fully suppressed, creating a THz QC amplifier. An optical gain as large as 30 dB was achieved from such an amplifier pumped with a separate QC laser, both held at a temperature of 4.5 K. Electron transport through the laser structure is determined by both radiative

and non-radiative transport mechanisms. The radiative transport (or photon-assisted transport) will increase as the photon density increases. For an amplifier without feedback, the photon density will be limited to weak spontaneous emission. Feedback will result in stimulated emission and possibly lasing, which will increase the photon density, and photon-assisted transport. If the amplifier is biased with a constant current, the enhanced transport due to the increase in photon density will lead to a voltage perturbation. At roll-off current point (J_{\max}) the maximum photon density coupled back will induce the maximum sensitivity, where an enhanced voltage perturbation was obtained compared with stand-alone lasers at the same bias condition. In our experiment, a voltage perturbation was achieved for a THz QC amplifier within the entire lasing dynamic range, from a threshold current (J_{th}) at 0.65 A to J_{\max} at 0.92 A, where over 100 mV enhancement was obtained at J_{\max} . This voltage perturbation presents the QC amplifier as an inherently sensitive device for self-mixing applications, where the maximum perturbation in voltage achieved for the QC amplifier is more than 30 times higher than the value obtained with a QC laser near the threshold point⁸. In addition, it allows the system to be operated in pulsed mode, which eases the limitation on the temperature of cw operation for a QC device, and further simplifies the imaging system by eliminating the need for a mechanical chopper or additional modulation signal. Furthermore, for self-mixing imaging this large voltage perturbation could in turn enable fast acquisition rates as a trade off with respect to the signal to noise ratio.

The THz QC amplifier used for this work is based on a 2.9 THz bound-to-continuum active region design as described in Ref. 19. The device was fabricated into a single plasmon geometry with a length of 1.9 mm and a width of 250 μm , where the active region was enclosed between a heavily doped bottom layer and a top metal contact²⁰. In order to adapt it into a QC amplifier and fully suppress the mirror losses, an antireflective-coated high-resistivity Si lens was applied by direct coupling to the facet of the device. The hyper-hemispherical Si lens had a diameter of 4 mm and an extension length of 2.67 mm. Parylene C (poly-monochoro-para-xylene) was employed as the antireflective coating layer, which has been demonstrated to suppress the reflectivity of a Si/air interface to

less than 3%²¹, and was sufficient to fully suppress the lasing action of a THz QC laser¹⁸. An 18.5 μm parylene C layer was deposited on the Si lens under vacuum conditions at room temperature. With the help of a thin layer of PMMA (polymethyl methacrylate) as the adhesive layer, the AR coated Si lens was attached to the facet of the laser without any other retaining contacts. Consequently, not only was a THz QC amplifier obtained, where the lasing oscillation was fully suppressed, but a less divergent out-coupling beam was also obtained due to the collimation from the hyper-hemispherical lens²². Two off-axis parabolic mirrors were employed to guide the beam from the amplifier to the target object, which was mounted on a pair of motorized linear translation stages, allowing for x-y motion in the focal plane of the mirror. The round-trip optical path between the QC amplifier and the object is 60 cm. All the measurements were performed at 4.5 K in a flow-helium cryostat. The QC amplifier was operated in pulsed mode with a 10-20 kHz repetition rate and a 6% duty cycle. The measurement setup is schematically presented in Fig. 1, where a second pulse generator was used to provide a constant calibration signal with a voltage output at the same duty cycle and repetition rate, and a value close to the voltage across the amplifier. The voltage across the QC amplifier (V_A) and the calibration signal from the second pulse generator (V_B), were filtered by band pass filters (3-30 kHz), and then fed into a low noise AC voltage amplifier, which provided a gain of 46 dB to the differential voltage signal ($V_A - V_B$). Finally, this amplified differential voltage signal was fed to a lock-in amplifier synchronized with the pulse generator fed to the QC amplifier. The lock-in signal was continuously sampled, as the object was scanned across the beam spot.

Two different cavity conditions were implemented in order to characterize the system sensitivity: where maximum optical feedback is achieved by using a flat mirror with a reflectivity of 99% serving as the feedback element at the focal point of the second parabolic mirror, and no optical feedback, where there was no target serving as the feedback element. This was achieved by moving the flat mirror in and out from the beam spot. The output intensity from the back facet of the QC amplifier was measured with a standard Golay cell detector. Due to the enhancement of the mirror loss from the antireflective-coated Si lens, with no

feedback element, the QC amplifier showed completely suppressed lasing action. Conversely, at the maximum feedback condition, the lasing oscillation was induced. From the voltage-current characteristics of the QC amplifier with different cavity conditions, voltage differences were observed above J_{th} as the amplifier lased in the condition of maximum feedback. This can be understood from the fact that, for a QC amplifier, feedback resulted in stimulated emission and lasing in this case, which increased the photon density and photon-assisted transport. As a result, this process created a voltage perturbation as shown in Fig. 2. As a result, the voltage across the device is in direct response to the external feedback, which can then be used to characterize the reflection of terahertz light off target objects.

Though a clear voltage perturbation across the QC amplifier was observed as shown in Fig. 2b, to achieve a better signal to noise ratio, a low noise voltage amplifier together with a lock-in amplifier were employed. The voltage of the second pulse generator was subtracted from the self-mixing induced voltage perturbation, which contained the information on the target objects, with the resulting signal being amplified by a differential amplifier. This amplified voltage signal was then measured by a lock-in amplifier, which was synchronized with the pulse generator to the QC amplifier. As shown in Fig. 2c, by plotting the differences of the lock-in signals at maximum feedback and no feedback conditions as described above, the lock-in signal perturbation was obtained that was a direct measure of the voltage perturbation across the QC amplifier. The sensitivity of the entire imaging system is defined as the signal to noise ratio of the measured lock-in signal perturbation. As is shown, a maximum signal to noise ratio over 55 dB was exhibited, where the standard deviation of the lock-in signal perturbation was about 0.2 mV below J_{th} . Plotted in Fig. 2d is the output power recorded by using a Golay cell detector. With the suppression of the mirror losses, the lasing oscillation was fully suppressed at the condition with no feedback. With the introduction of the feedback, the lasing action was rebuilt, where the maximum amount of radiation coupled back into the QC amplifier is estimated to be ~ 1.2 mW at J_{max} ²³. At J_{max} , not only maximum photon emission but also minimal differential resistance of the device were exhibited.

Consequently maximum voltage perturbation was obtained at J_{\max} for the QC amplifier when the feedback was introduced. As a result, the J_{\max} for the QC amplifier from the power measurement also presented the best sensitivity region where the maximum voltage perturbation occurred. Correspondingly, the lock-in signal perturbation curve also exhibited the same dynamic range as the output power curve.

By inserting apertures of different diameters into the imaging system at the focal point of the second parabolic mirror, characterization of the entire system was performed, including the sensitivity and resolution. The apertures employed were fabricated on Al substrates, with a layer of absorber as described in Ref. 24. The object was placed behind the aperture at a distance of ~ 1 mm. As shown in Fig. 3a, the lock-in signals, which were measures of the voltage perturbation across the QC amplifier as a function of the external feedback, represented the system sensitivity. A K factor was defined as a figure-of-merit of an imaging system⁷ $K = (V_s - V_b) / \sigma_b$, where in our case V_s is the lock-in signal with maximum feedback, V_b is the lock-in signal with no feedback and σ_b is the standard deviation of V_b . At the J_{\max} of the QC amplifier with 6% duty cycle at 10 kHz repetition rate, for the scheme with maximum feedback condition without using any aperture, we obtain a value of $K = 865$, which is about 5~6 times higher than the previous value reported by self-mixing results from a THz QCL operating at J_{th} . This superior K factor is mainly due to the enhanced voltage perturbation from the maximum photon density coupled back, leading to the enhancement of photon-assisted transport at J_{\max} for the QC amplifier. By scanning a chrome ridge target on a glass substrate across the beam spot, the resolution of the imaging system could be determined by measuring the modulation transfer function⁸. As can be extracted from the data in Fig. 3b, with the smallest aperture (0.7 mm), our system is capable of resolving features down to ~ 300 μm , by defining the resolution limit at 10% modulation threshold. The K factor dropped with the reduction of the beam spot sizes, where a value of $K = 320$ was obtained with this smallest aperture condition. This K factor could be improved by increasing the duty cycle of the feeding pulses to the QC amplifier as shown in Fig.

3C, where 40% higher sensitivity was obtained with the duty cycle enhanced to 10%, as it reached to the limit of the biasing circuit we employed.

Imaging was obtained by monitoring the lock-in signal perturbation across the QC amplifier, with an object scanned across the beam spot behind the aperture. The resulting images are shown in Fig. 4, where the 0.7 mm aperture was used to define the illuminated area on the target. High-resolution images of a gold coin with a diameter of 16.5 mm have been obtained. The sensitivity was high enough to enable acquisition of 20,000 points per second. As shown in Fig. 4a, a high-resolution, well resolved image was obtained with a 1 μm step size, a 10 μs time constant for the lock-in amplifier and a 20,000 pps scan rate. This acquisition rate was currently only limited by the speed of the analog to digital converter we employed. However, to achieve a better signal to noise ratio, scans with different lock-in amplifier time constants of 320 μs and 10 ms were taken as shown in Fig. 4 b and c, where the acquisition rates were 1000 pps and 40 pps, respectively. Moreover, an optical mask with letters of 'CAVENDISH LABS' was also employed as the target object, where the background was chrome and the letters were open areas in the glass substrate. The images show the magnitude of the lock-in signal obtained from the perturbation voltage across the amplifier, which was a result of the different reflectivity of the glass substrate and chrome surface. A well resolved image was obtained, where the width of the letters was only 150 μm .

We have developed a terahertz imaging system based on the self-mixing effect of a quantum cascade amplifier. With the help of the additional optical feedback to the QC amplifier, due to photon-assisted transport, prominent sensitivity was achieved with the device operated in pulsed mode. Consequently, combined with fast data acquisition rate, a high-resolution image with 20,000 points was obtained within only 1 second.

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Fig. 1, Schematic diagram of the imaging setup. Two off-axis parabolic mirrors (effective focal length: 101.6 mm) are employed to guide the beam from the amplifier to the target object. The biasing signal to the QC amplifier is produced by a pulse generator, and the calibration signal is generated with another synchronized pulse generator. The voltage signal across the QC amplifier and this calibration signal are filtered by bandpass filters with a bandwidth from 3-30 kHz, to provide the best signal to noise ratio. The two filtered signals are then amplified by a low noise AC amplifier with a gain of 46 dB on the differential signal of the two inputs, and further fed to a lock-in amplifier. Eventually the lock-in signal is recorded at constant time intervals while the target object is scanned with a pair of motorized linear stages.

Fig.2, Characterizations of the QC amplifier operated in pulsed mode with a 10 kHz repetition rate and a 6% duty cycle. **a**, Voltage of the QC amplifier as a function of the current with maximum feedback (blue dashed line) and with no feedback (red line) conditions. **b**, The voltage perturbation across the QC amplifier at maximum feedback and no feedback conditions. **c**, The lock-in signal perturbation at maximum feedback and no feedback conditions. **d**, The output intensity of the QC amplifier recorded by a Golay cell detector from the back facet. The blue dashed line is the measured data for the QC amplifier with a flat mirror as the feedback element for the maximum feedback condition and the red line represents the output power with no feedback where the lasing oscillation is fully suppressed.

Fig. 3, **a**, Lock-in signal response measured at the J_{\max} for the QC amplifier in pulsed mode with a 10 kHz repetition rate and a 6% duty cycle, as a function of the aperture size, chopped between two conditions: with maximum feedback and with no feedback. **b**, Modulation transfer function of the imaging system with different aperture sizes measured at the J_{\max} for the QC amplifier in pulsed mode with a 10 kHz repetition rate and a 6% duty cycle. The red line (0.7 mm aperture) indicates the system is capable of resolving features down to the width of $\sim 300 \mu\text{m}$. **c**, Normalized lock-in signal response as a function of the duty cycle of the feeding pulse to the QC amplifier measured at the J_{\max} in pulsed mode with a 10 kHz repetition rate.

Fig. 4, Imaging of a Lunar Year of the Horse 2014 Gold Coin with a diameter of 16.5 mm obtained with the QC amplifier at the J_{\max} in pulsed mode with 6% duty cycle **a**, Single frame image with 20,000 pps acquisition rate obtained with the QC amplifier operated with a 20 kHz repetition rate, a 10 μs time constant for the lock-in amplifier, a step size of 1 μm , and a 3 min acquisition time. **b**, Single frame image with 1,000 pps acquisition rate obtained with the QC amplifier operated with a 20 kHz repetition rate, a 320 μs time constant for the lock-in amplifier, a step size of 10 μm , and a 7 min acquisition time. **c**, Single frame image with 40 pps acquisition rate obtained with the QC amplifier operated with a 10 kHz repetition rate, 10 ms time constant for the lock-in amplifier, a step size of 25 μm , and a 220 min acquisition time. The scale bar represents the lock-in signal response in the plot. **d**, A high-resolution image of an optical mask with letters of 'CAVENDISH LABS', where the background was chrome and the letters were an open area of the glass substrate. The step size is 20 μm with 33 pps acquisition rate and 10 ms time constant for the lock-in amplifier, with the QC amplifier operated at the J_{\max} in pulsed mode with a 10 kHz repetition rate and 6% duty cycle.







